Towards Higher Adaptive Capacity in Urban Water Management (RAINMAN, KS 1038) international project within the South-East Finland - Russia Cross-border Cooperation 2014-2020 Programme.

Major interim conclusions and outputs obtained in the development of recommendations for St.Petersburg wastewater disposal systems adaptation to changing climate conditions and urban environment improvement level.

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1. Hydraulic dynamic modeling results revealed that there are two mechanisms of St.Petersburg territory flooding:

- the first is enabled with the network sections capacity insufficiency. In this case, the water rises to the surface on the sections “tail areas”, fig. 1.

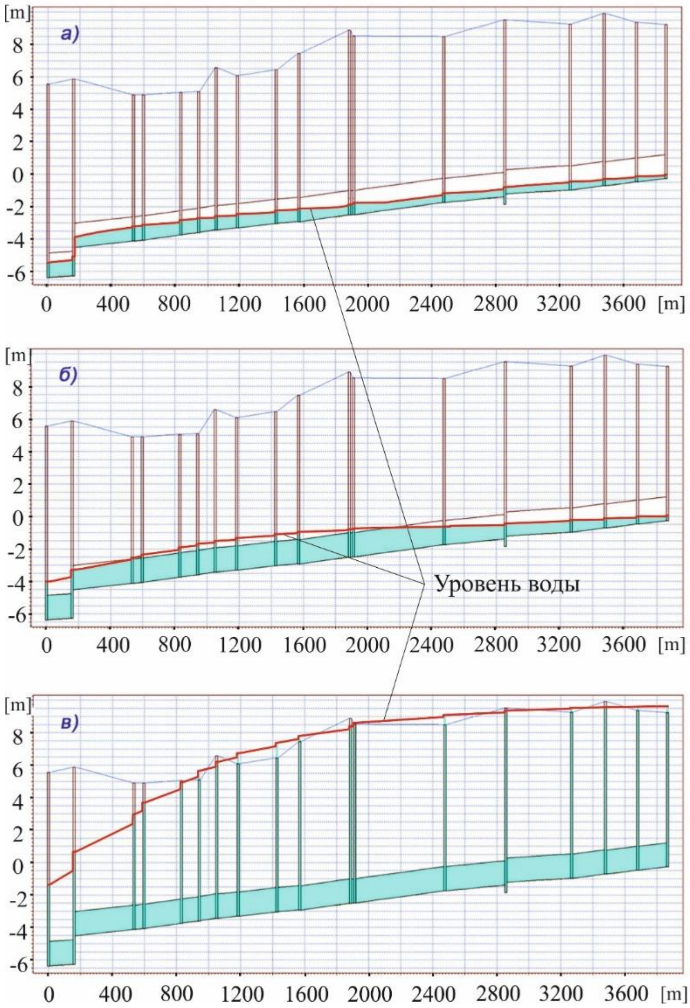

Fig. 1. The mechanism of gravity sewer collector flooding when the wastewater inflow exceeds its capacity as a result of the wastewater off-nominal inflow along its length: *a* – collector profile and filling at the nominal wastewater inflow *q*; *b* – same, but with a *2q* inflow; *c* – same, but with a 3,5*q* inflow

- the second is enabled by the pumping stations operation insufficiency. In this case, water rises to the surface on the “head areas”, fig. 2.

Simultaneous occurrence of both mechanisms is possible, fig. 3.

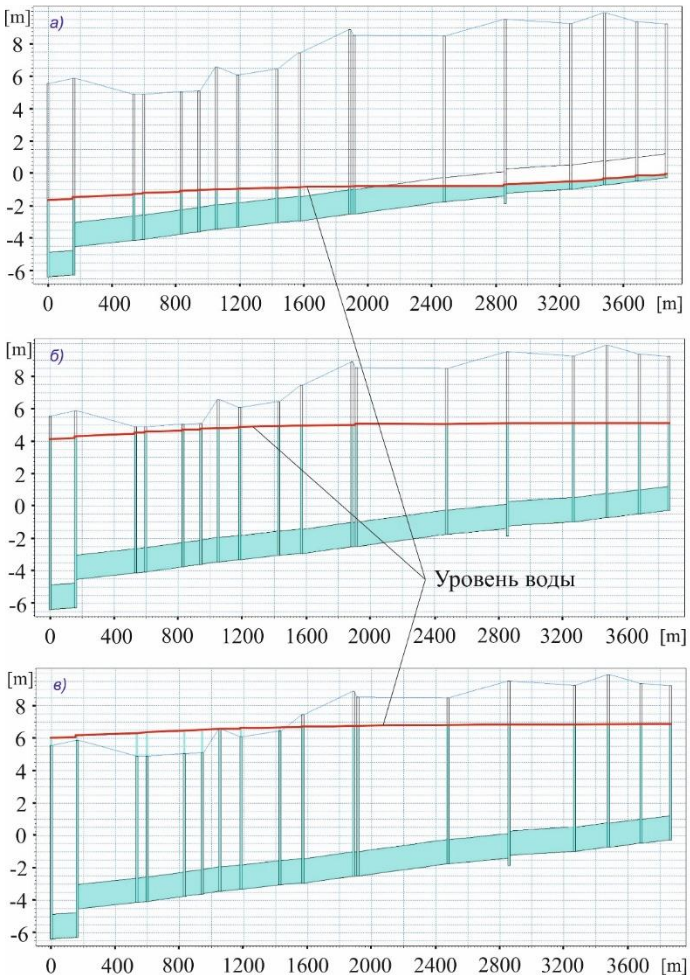

Fig. 2. The mechanism of gravity sewer collector flooding in case of a piezometric head and closing the valve gate in front of the SPS as a result of an off-nominal inflow of wastewater along the collector length: *a* – collector profile and filling with head H_{head}=3D_{col} and a valve gate opening degree H_{gate}= 100%; *b* – same, but with H_{head}=3D_{col} and H_{gate}= 15%; *c* – same, but with H_{head}=3D_{col} and H_{gate}= 10%

2. To determine the wastewater disposal systems sensitivity to the current climate change conditions, a program-method of hydraulic modeling has been developed, which includes: substantiation of representative catchment areas for wastewater disposal systems sensitivity to the current climate change conditions survey; hydraulic calculation of wastewater disposal networks of representative catchment areas in accordance with the standards in force at the time of their designing; substantiation of parameters and course of nominal rainfall for hydraulic modeling; hydraulic modeling of representative catchment areas, fig. 4.

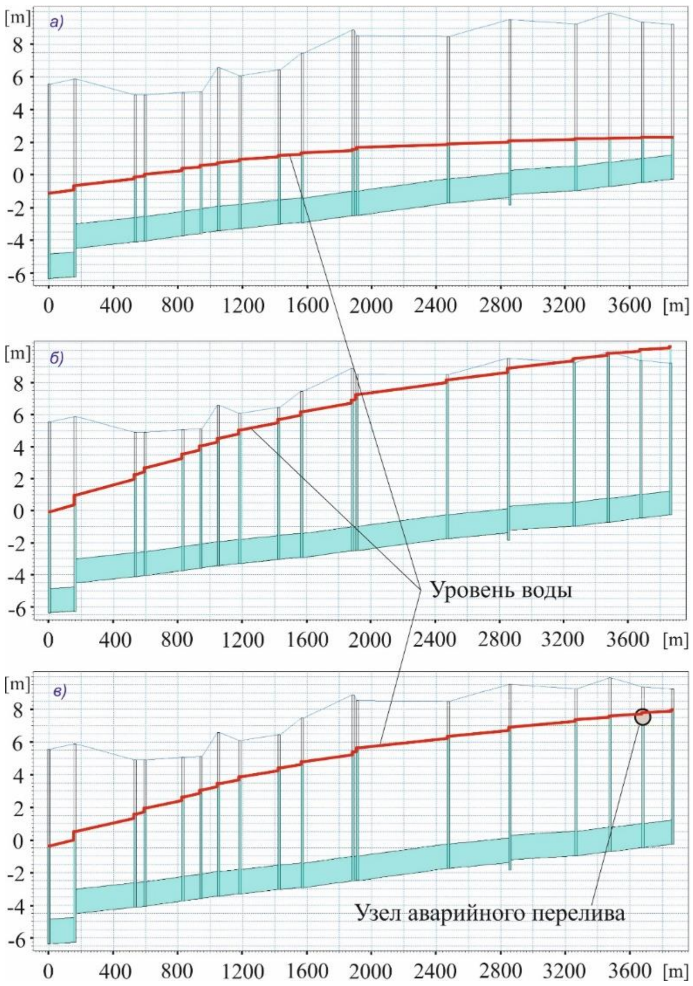

Fig. 3. The mechanism of gravity sewer collector flooding with a simultaneous excess of the wastewater inflow over its capacity and closing a valve gate in front of the SPS as a result of an off-nominal inflow of wastewater: *a* – collector profile and filling with head H_{head}=3D_{col}, valve gate opening degree H_{gate}= 75% and inflow 2*q*; *b* – same, but with H_{head}=3D_{col} and H_{gate}= 65% and inflow 2,5*q*; *c* – same, but with emergency overflow unit

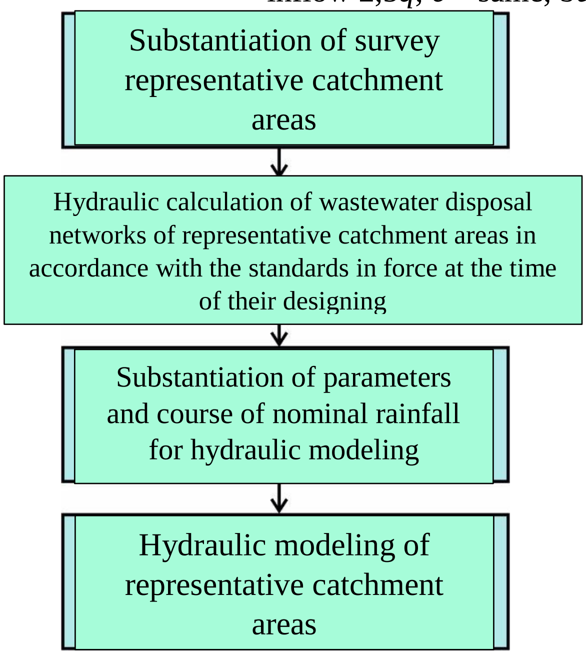

Fig. 4. Program-method of hydraulic modeling

3. Distribution assessment of all St.Petersburg wastewater disposal networks was performed, depending on the regulatory framework for their design. The research results are given in Fig. 5. It shows that most of the wastewater disposal networks are designed according to TUiN 1954, SNiP II-G.6-62, SNiP P-32-74, SNiP 2.04.03-85, SP 32.13330.2012. Therefore, the hydraulic modeling was carried out with the examples of representative catchment areas, calculated according to these standards.

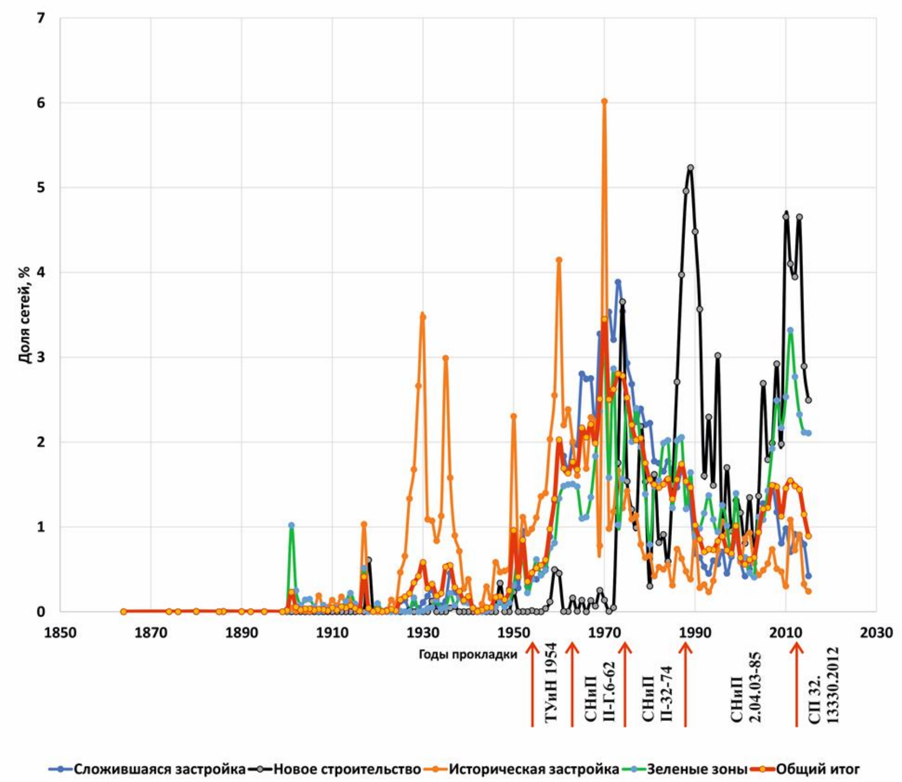

Fig. 5. Results of St. Petersburg wastewater disposal networks distribution survey depending on the regulatory framework for their design

Hydraulic calculations for all the listed regulatory documents were performed using the limit intensities method (rational method modification). Selected results of hydraulic modeling are shown in Fig. 6-10. In general, the obtained results analysis indicates imperfection all the calculated climatic parameters (q_{20}, n, m, γ) for St. Petersburg and confirms the need for their reconsideration, where: q_{20} - is the intensity of 20 minutes rainfall for a given area with a period of one time exceeding of the calculated rain intensity, P = 1 year; m - is the average amount of rainfall per year; n, γ - empirical parameters.

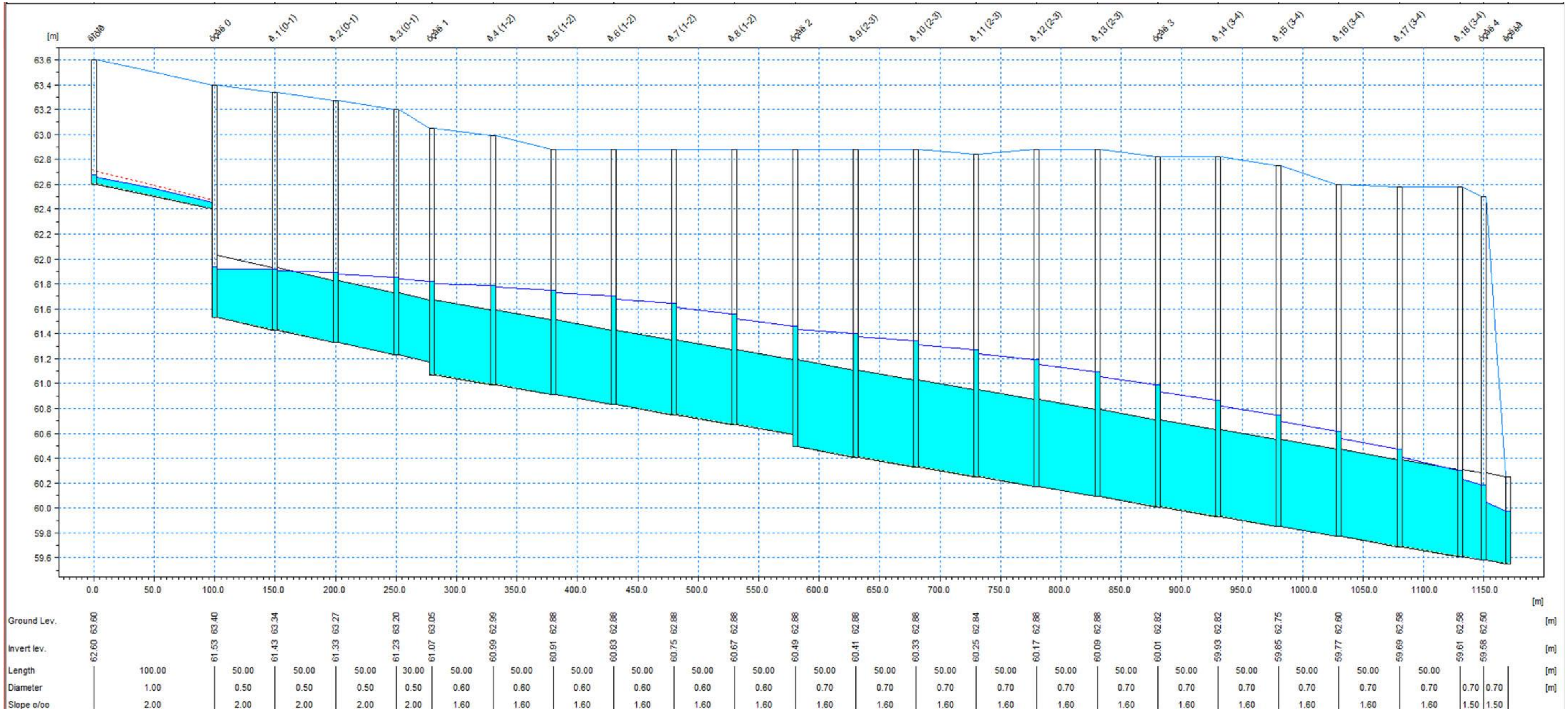

Fig. 6. Results of hydraulic modeling of network, calculated for p = 0.33 according to TUiN 1954, SNiP II-G.6-62 with nominal rainfall, taking into account the resistance in wells

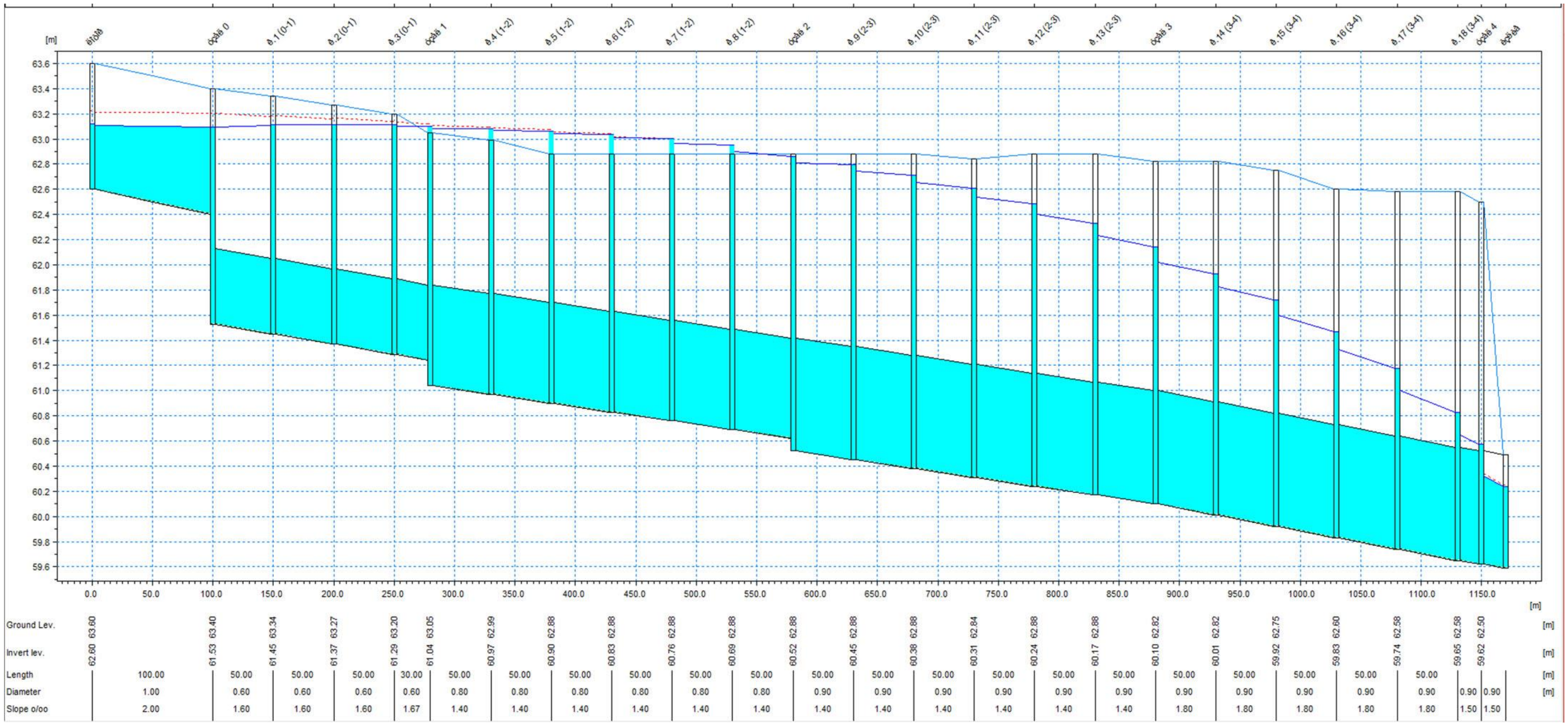

Fig. 7. Results of hydraulic modeling of network, calculated for p = 1 according to TUiN 1954, SNiP II-G.6-62 with nominal rainfall, taking into account the resistance in wells

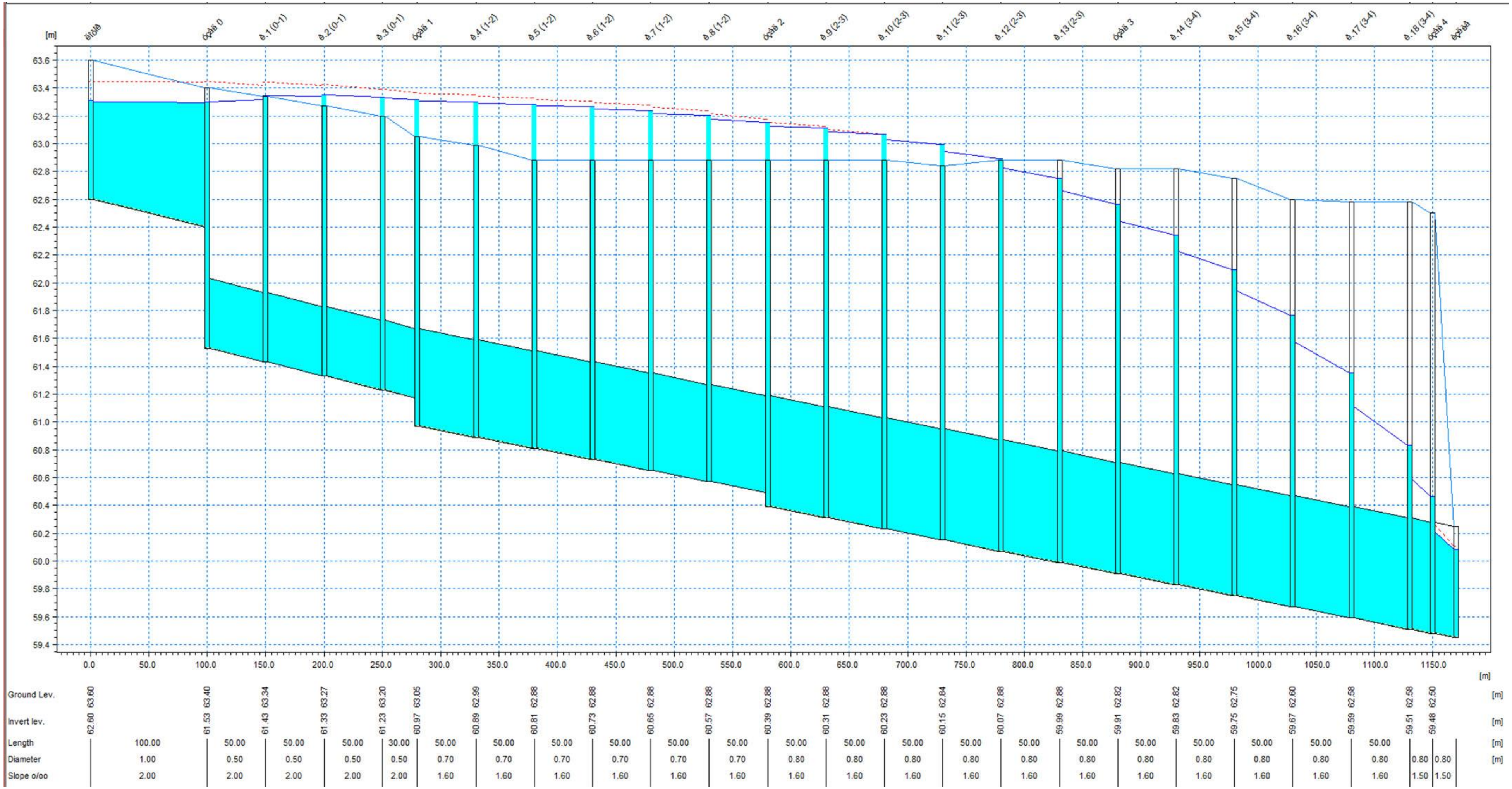

Fig. 8. Results of hydraulic modeling of network, calculated for p = 0.33 according to SP 32.13330.2012 with off-nominal rainfall (p=1), taking into account the resistance in wells

4. The assessment of the application reliability of primary information on rainfall in St. Petersburg, accumulated in Roshydromet for five years (from 2015 to 2020) using 34 self-recording rain gauges with a 5 minutes operational interval, as a database to update the local climatic parameters, applied in the current codes of practice for the design of surface runoff disposal systems. It was found that the rainfall patterns revealed over 5 years do not contradict the classical theory. At the same time, they, in contrast to the results of processing long-term data at one point, more fully reflect the features of uneven distribution of precipitation over the megalopolis territory, Fig. 9;

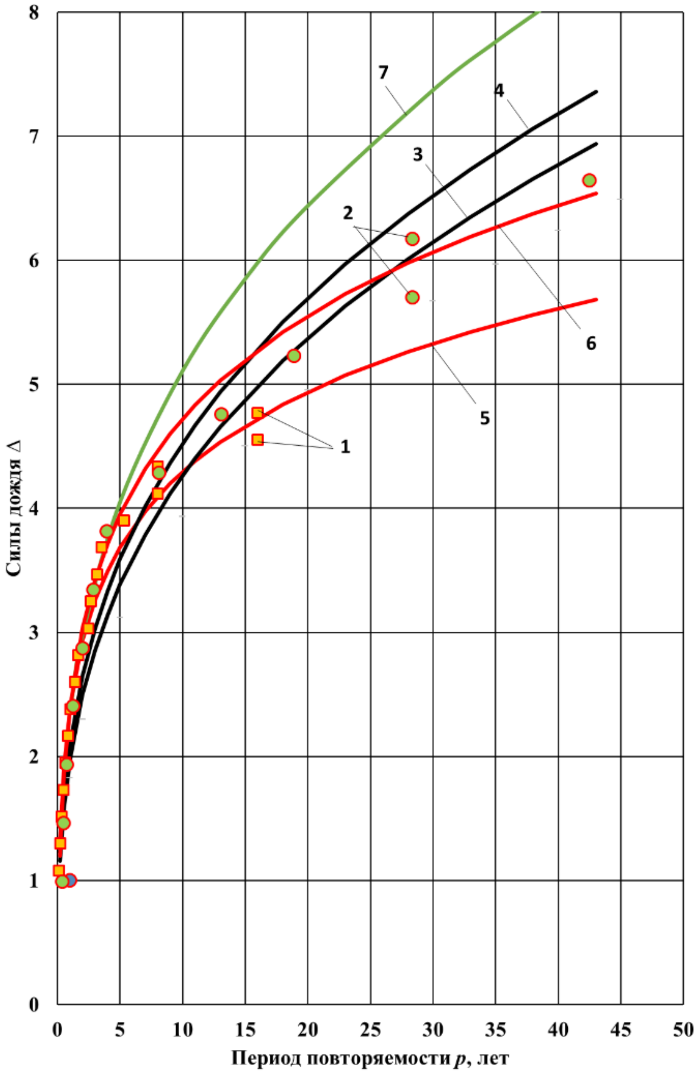

Fig. 9. Results of various climatic dependences assessment methods and their parameters comparison: *1* - data of N.N. Belov at one point for the period from 1897 to 1928; *2* - averaged data from Roshydromet at 34 points for the period from 2015 to 2020; *3* - results of N.N. Belov’s data approximation; *4* - same for Roshydromet data; *5*- results of N. N. Belov’s data approximation according to the logarithmic dependence; *6* - same for Roshydromet data; *7* - according to the formula of prof. P.F. Gorbachev and depending on the total annual precipitation

5. The dynamics of changes in the total daily precipitation *H* in St.Petersburg from 1881 to 2019 was analyzed, see Fig. 10. Based on these data, the rainfall rates were determined. Their analysis showed that at p=0.33, the

increase in rainfall Δ reaches approximately 0.19% per year. Therefore, for networks designed and laid 50 years ago, the actual change in this parameter will equal 9 – 9,5%.

6. As a result of studies carried out with a verified hydraulic dynamic model of a representative surface runoff disposal system, it was found that climate changes resulted in about 26% increase of water flow in the calculated periods with an increase in its total volume by 9-10%, Fig. 11.

7. The characteristics of four typical development zones were developed, taking into account the runoff rates average values, catchment area, specific regulating volume and coefficient of regulating volume use, table 1.

Table 1. General characteristics for four typical development zones of St.Petersburg

Zone No.	Zone name	Runoff rate	Catchment area, ha	k_v coefficient of regulating volume use	Specific regulating volume V_{sp}, m3/ha
1	New construction	0.27	1,126	0.5	21.7
1.1	Part 1	0.22	471	0.5	20
1.2	Part 2	0.38	655	0.5	25
2	Existing development	0.42	1,157	0.8	30
3	Green areas	0.21	509	0.6	18
4	Historical development	0.67	121	0.8	36

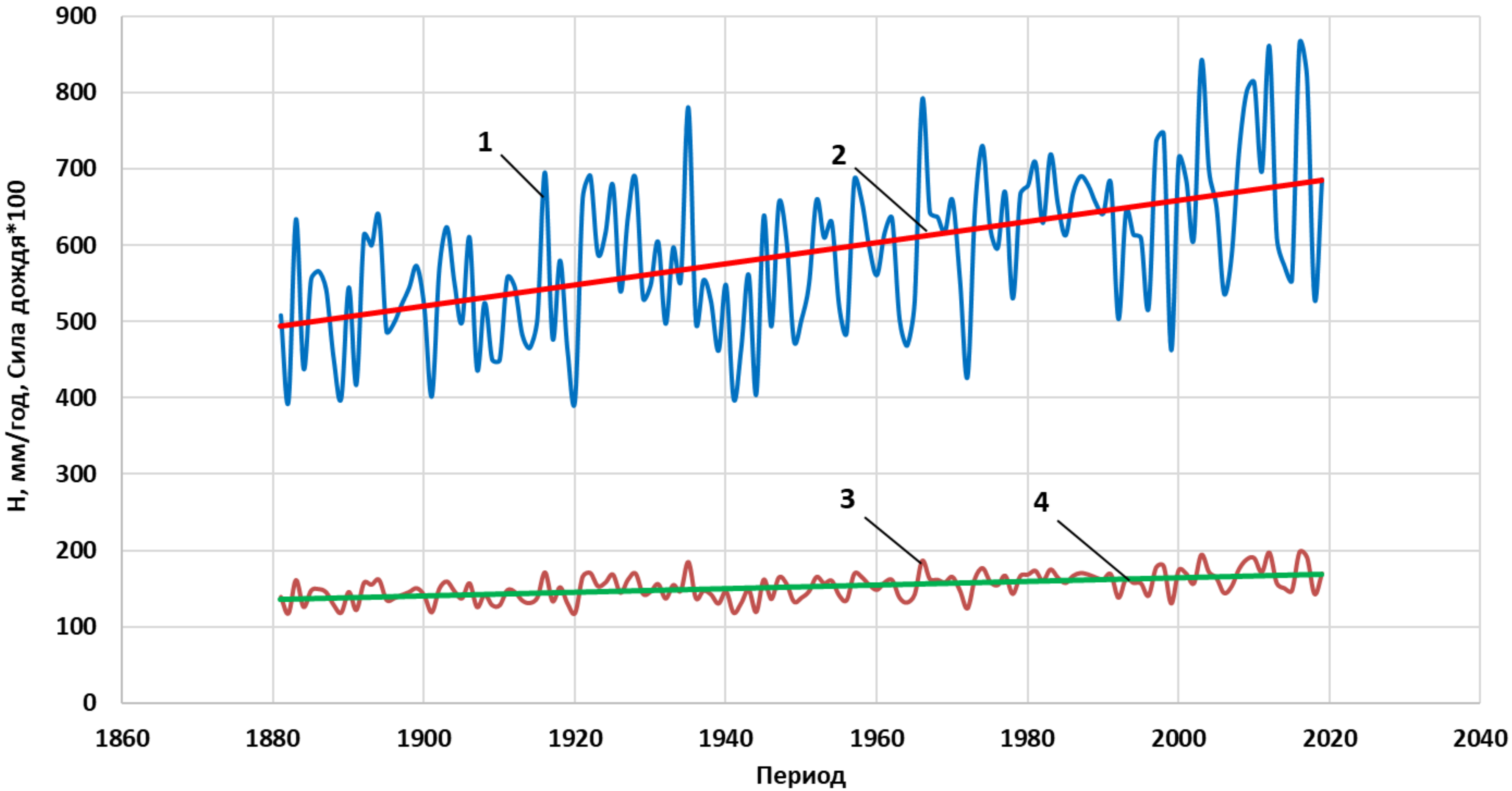

Fig. 10. Dynamics of changes in total annual precipitation *H* and rain force Δ in St.Petersburg from 1986 to 2019: *1* – data processing results of the FBGU Voeikov Main Geophysical Observatory and Roshydromet on the annual precipitation change *H*; *2* –results of linear approximation of data *H*; *3* – calculated values of changes in rain forces Δ; *4* – results of linear approximation of data Δ

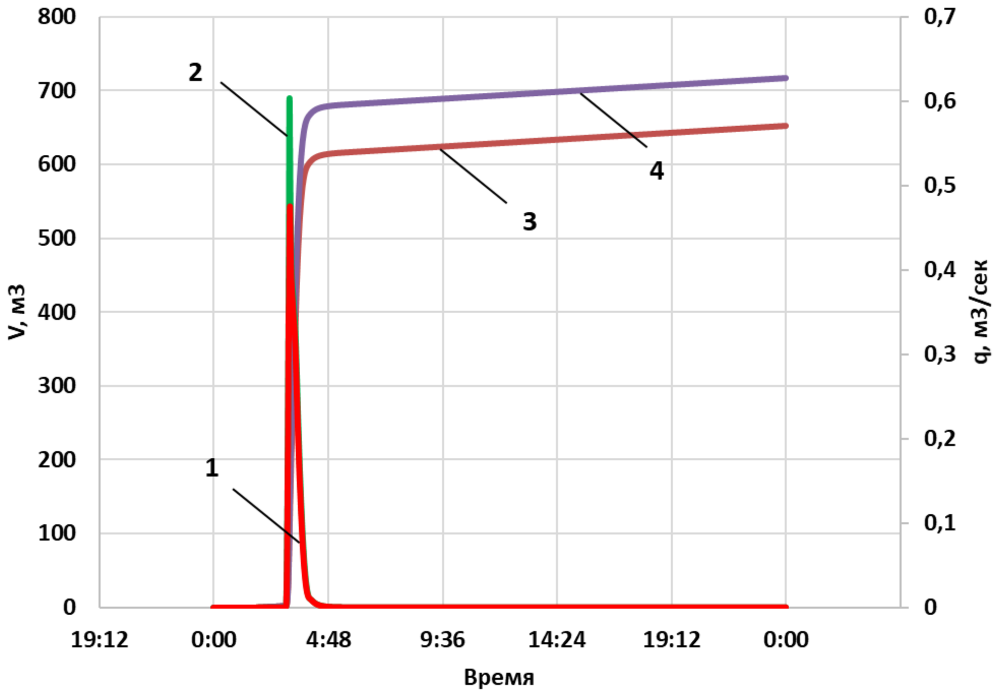

Fig. 11. Results of changes in the hydraulic regimes of runoff inflow: *1* – runoff flow for the design period as a result of nominal rainfall; *2*– same for actual nominal, in 50 years; *3* – runoff volume during the nominal rainfall for the design period; *4*– same, in 50 years

8. Assessment of the average annual estimated amount of St.Petersburg territories flooding as result of the occurrence of pressure regimes in the wastewater disposal systems for the formulated characteristics of four typical development zones has been carried out. The results are shown in table 2. Here, flooding means events that occurred solely due to the occurrence of off-nominal rains with a wide range of the water surfacing duration. Therefore, the shortest of them, as a rule, are not recorded and do not fall into the official statistics.

Table 2. General results of assessing the St.Petersburg territories flooding frequency

Typical development zones	Runoff rate	V_{sp}	k_v	$k_v * V_{sp}$	Flooding period p		Network share, %	Average number of floods per year at p		Total
					0.33	1		0.33	1	
New construction 1	0.22	20	0.5	10	2	11	5	3	1	**4**
New construction 2	0.38	25	0.5	12.5	1	7	2	2	0	**2**
Existing	0.42	30	0.8	24	3	15	58	22	4	**26**
Green areas	0.21	18	0.6	10.8	3	10	21	8	2	**10**
Historical development	0.67	36	0.8	28.8	2	8	14	8	2	**10**
Total							**100**	**43**	**9**	**52**

9. Classification of mechanisms for eliminating flooding in St. Petersburg has been elaborated in order to develop recommendations for eliminating flooding in the most vulnerable areas with centralized wastewater disposal systems. It additionally includes two new mechanisms from HELCOM Draft Recommendations 23/5: stormwater diversion to low-lying areas and systems design for future climate change scenarios, Fig. 12.

10. An analysis of regulatory and legislative documents showed that the mechanism associated with the runoff diversion to low-lying areas in the Russian Federation is practically impossible, since discharge of wastewater, including treated, onto the terrain is not legally regulated in our country. There is no explicit ban, but Rosprirodnadzor does not give permission for this either. The question is open. Surface runoff can only be discharged into water bodies or centralized wastewater disposal systems.

11. System design mechanism, taking into account future climate change scenarios, introduction in the Russian Federation requires refining the regulatory framework, since the current Codes of Rules climatic parameters, which are applied to calculate rains intensity, do not take into account future climate change scenarios, but moreover use 35-years old data to determine the current ones. Since it is impossible to act on a national scale, as it was done before, it is advisable to develop and approve this mechanism at a regional methodological document level for St. Petersburg.

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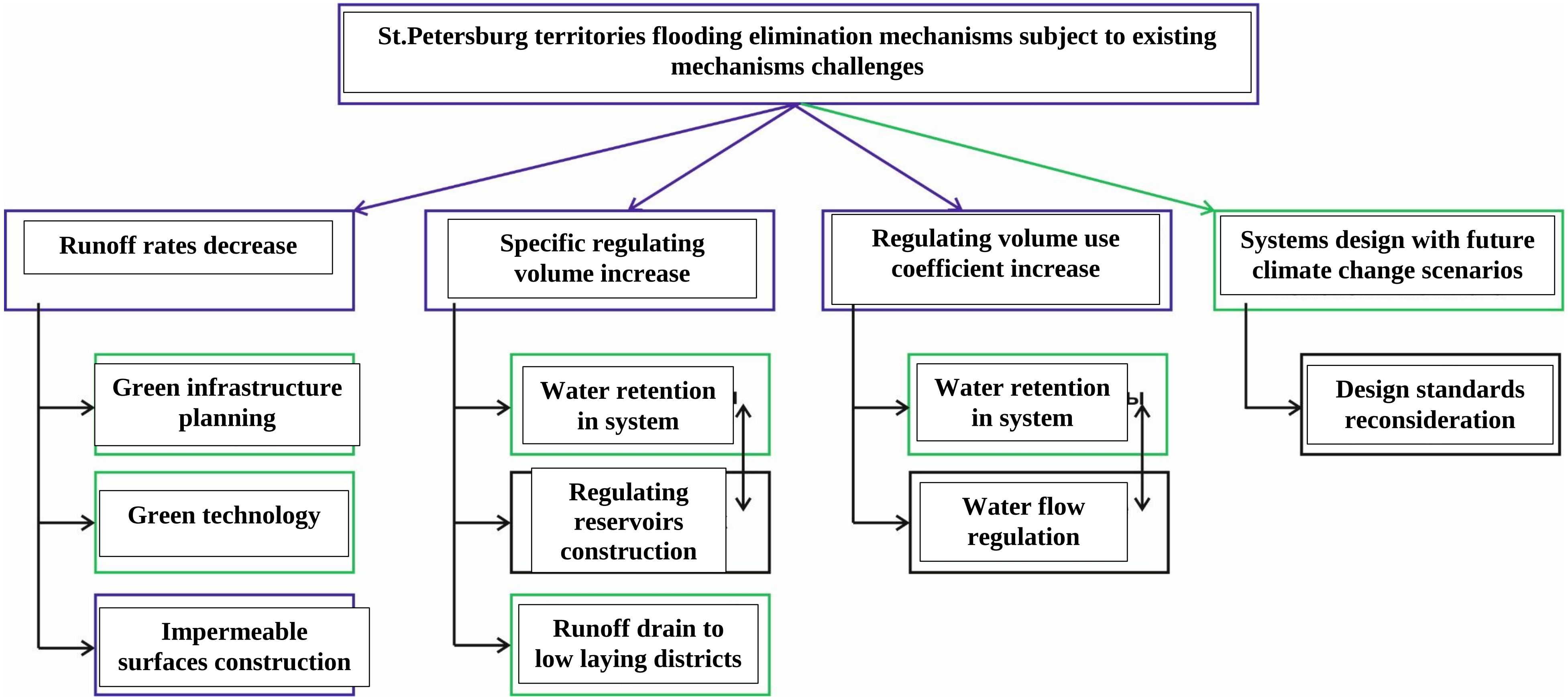

Fig. 12. Classification of mechanisms for flooding eliminating in St. Petersburg

12. The performance of increasing the k_v coefficient of the regulating volume volumetric use for the new construction and green areas zones is analyzed. The results are shown in table 3. It indicates that this measure allows reducing the average annual number of floods from 43 to 37.

Table 3. Overall results of assessing changes in the St.Petersburg territories flooding frequency as a result of an increase in the coefficient k_v of the volumetric use of regulatory volume

Typical development zones	Runoff rate	V_{sp}	k_v	$k_v * V_{sp}$	Flooding period p		Network share, %	Average number of floods per year at p		Total
					0.33	1		0.33	1	
New construction 1	0.22	20	**0.8**	16	5	30	5	1	0.19	1.19
New construction 2	0.38	25	**0.8**	20	2.1	12	2	1	0.19	1.19
Existing	0.42	30	0.8	24	3	15	58	22	4.41	26.41
Green areas	0.21	18	**0.8**	14.4	5	24	21	5	0.99	5.99
Historical development	0.67	36	0.8	28.8	2	8	14	8	1.99	9.99
Total							**100**	**37**	**7.77**	**46.37**

13. The performance of increasing the k_v coefficient of the regulating volume volumetric use and specific regulating volume for the new construction and green areas zones is analyzed. The results are shown in table 4. It indicates that this measure allows reducing the average annual number of floods from 43 to 32.

Table 4. Overall results of assessing changes in the St.Petersburg territories flooding frequency as a result of an increase in the coefficient k_v of the volumetric use of regulatory volume and specific regulating volume

Typical development zones	Runoff rate	V_{sp}	k_v	$k_v * V_{sp}$	Flooding period p		Network share, %	Average number of floods per year at p		Total
					0.33	1		0.33	1	
New construction 1	0.22	**30**	**0.8**	24	21	70	5	0	0.08	0.08
New construction 2	0.38	**30**	**0.8**	24	3.8	21	2	1	0.11	1.11
Existing	0.42	30	0.8	24	3	15	58	22	4.41	26.41
Green areas	0.21	**30**	**0.8**	24	30	70	21	1	0.34	1.34
Historical development	0.67	36	0.8	28.8	2	8	14	8	1.99	9.99
Total							**100**	**32**	**6.93**	**38.93**

14. The performance of increasing the k_v coefficient of the regulating volume volumetric use and specific regulating volume, as well as reducing the flow rate for the new construction, existing and historical buildings zones is analyzed. The results are shown in table 5. It indicates that this measure allows reducing the average annual number of floods from 43 to 27.

Table 5. Overall results of assessing changes in the St.Petersburg territories flooding frequency as a result of an increase in the coefficient k_v of the volumetric use of regulatory volume, specific regulating volume and runoff rate decrease

Typical development zones	Runoff rate	V_{sp}	k_v	$k_v * V_{sp}$	Flooding period p		Network share, %	Average number of floods per year at p		Total
					0,33	1		0,33	1	
New construction 1	0.22	**30**	**0.8**	24	21	70	5	0	0.08	0.08
New construction 2	**0.3**	**30**	**0.8**	24	6.5	41	2	0	0.056	0.056
Existing	**0.3**	30	0.8	24	3	15	58	22	4.41	26.41
Green areas	0.21	**30**	**0.8**	24	30	70	21	1	0.34	1.34
Historical development	**0.4**	36	0.8	28.8	5	25	14	3	0.64	3.64
Total							**100**	**27**	**5.53**	**32.53**

In general, the performed analysis shows that the considered measures application allows, on the big city scale, to reduce the average number of flooding by about 35-40%. Of these, the most effective measures are related to the regulatory volumes increase. Therefore, if a more significant reduction in the amount of flooding is required, then there is a need for overall reconstruction of the operating surface runoff disposal systems. However, its combination with assessed engineering measures will reduce the cost, construction time and design capacity of treatment plants.

15. It has been established that the introduction of a specific regulatory volume additional increase mechanism is generally advisable to implement through the construction of regulatory reservoirs. Subject to the normative methodologies, it is necessary to carry out verification dynamic modeling to assess the actual regulation coefficients following to the reservoirs size justifying. The need for this

measure follows the imperfection of reservoirs calculation regulatory methods, and outdated calculation parameters of rainfall.

16. It has been established that it is advisable to introduce a regulating volume utilization rate increasing mechanism with the help of emergency overflow units that drain water into the underlying areas. At the same time, in order to increase the regulation performance, it is advisable to build not one regulating reservoir, but several, of a reduced volume, located at different points of a catchment area. This will minimize the mechanism emerging challenges.

17. Wastewater catchment areas operation in the most vulnerable territories of St. Petersburg modeling was performed to analyze the wastewater disposal systems adaptation mechanisms application results in face of climate change and taking into account St.Petersburg territorial development prospects.

18. Calibration of the calculated hydraulic models was performed with field measurements of flow rates, wastewater flows and levels during periods of dry weather and during periods of precipitation using 3 non-contact radar flow meters (No. 14220431410, 14220431412, 14220431413), electromagnetic velocity meter (No. 14220431411) and gravity flow meter (No. 14220431422), purchased by SUE “Vodokanal of St.Petersburg” with the Rainman KS-1038 project grant funds, fig. 13 – 15.

Fig. 13. Velocity meter

Fig. 14. Flowmeter

Fig. 15. Flowmeter-level gauge

19. The calibration results show that in “dry” weather the modelled flow rates values are slightly less than the actual ones, which confirms the presence of infiltration in the networks, and contrary situation is observed during the rainy season, as, probably, the surface concentration duration differs from the calculated one.

20. The modelling results show that, in pressure modes resistances in nodes, which is not taken into account by Russian design standards, play an important role along with climate change.

21. The modelling results allow us to draw the following conclusions:

- an increase in the specific regulating volume and increase in the utilization rate of the regulating volume with a systematic approach are effective mechanisms for eliminating flooding;

- their application allows to reduce the maximum wastewater flow by 60% on average in individual catchment areas and increase the duration of water outflow by 80 - 100%.